METHOD AND SYSTEM FOR FABRICATING NANOSCALE PATTERNS IN LIGHT CURABLE COMPOSITIONS USING AN ELECTRIC FIELD

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention generally relates to the area of low cost, high-resolution, high-throughput lithography with the potential to make structures that are below 100nm in size.

2. Description of the Relevant Art

[0002] Optical lithography techniques are currently used to make microelectronic devices. However, these methods are reaching their limits in resolution. Sub-micron scale lithography has been a critical process in the microelectronics industry. The use of sub-micron scale lithography allows manufacturers to meet the increased demand for smaller and more densely packed electronic components on chips. The finest structures producible in the microelectronics industry are currently on the order of about 0.13 µm. It is expected that in the coming years, the microelectronics industry will pursue structures that are smaller than 0.05 µm (50 nm). Further, there are emerging applications of nanometer scale lithography in the areas of opto-electronics and magnetic storage. For example, photonic crystals and high-density patterned magnetic memory of the order of terabytes per square inch require nanometer scale lithography.

[0003] For making sub-50 nm structures, optical lithography techniques may require the use of very short wavelengths of light (for instance 13.2 nm). At these short wavelengths, few, if any, materials are optically transparent and therefore imaging systems typically have

to be constructed using complicated reflective optics [1]. Furthermore, obtaining a light source that has sufficient output intensity at these wavelengths of light is difficult. Such systems lead to extremely complicated equipment and processes that appear to be prohibitively expensive. High-resolution e-beam lithography techniques, though very precise, typically are too slow for high-volume commercial applications.

[0004] One of the main challenges with current imprint lithography technologies is the need to establish direct contact between the template (master) and the substrate. This may lead to defects, low process yields, and low template life. Additionally, the template in imprint lithography typically is the same size as the eventual structures on the substrate (1X), as compared to 4X masks typically used in optical lithography. The cost of preparing the template and the life of the template are issues that may make imprint lithography impractical. Hence there exists a need for improved lithography techniques that address the challenges associated with optical lithography, e-beam lithography and imprint lithography for creating very high-resolution features.

SUMMARY OF THE INVENTION

[0005] In one embodiment, patterned structures may be created on a substrate using imprint lithography. The process involves applying a polymerizable composition to the upper surface of the substrate. The substrate may be a substrate used to prepare a semiconductor device. Examples of substrates include, but are not limited to, Si wafers, GaAs wafers, SiGeC wafers, or an InP wafers. The polymerizable composition may be an ultraviolet light curable composition. The ultraviolet light curable composition may include a polymerizable monomer and a

photo initiator. The composition may be spin coated onto the substrate.

[0006] After the substrate has been coated with the polymerizable composition a template may be placed above the polymerizable composition. The template is formed from an electrically conductive material. The template may also be substantially transparent to visible and/or ultraviolet light. The template may be formed of a combination of an electrically conductive material coupled to a non-conductive material. Both the electrically conductive material and the non-conductive material may be substantially transparent to light. In one embodiment, the template may be formed of indium tin oxide and fused silica. The template includes a pattern of structures. The pattern of structures are complimentary to the pattern of structures which are to be produced on the substrate. At least a portion of the structures may have a feature size of less than about 100 nm.

[0007] An electric field may be applied between the template and the substrate. The application of the electric field may create a static force that attracts at least a portion of the polymerizable composition toward the template. The portions of the polymerizable composition that are attracted to the template are complementary to the pattern of structures imprinted on the template. In one embodiment, the portions of the polymerizable composition that are attracted to the template come into contact with the template, while the remaining portions do not contact the template. Alternatively, neither the attracted portions nor the remaining portions of the polymerizable composition come into contact with the template. The attracted portions,

however, extend toward the template while the un-attracted portions do not extend to the same extent that the attracted portions extend toward the template.

[0008] The polymerizable composition may be polymerized using an appropriate curing technique. For example, the polymerizable composition may include a photoinitiator and be curable by exposure to activating light while an electric field is applied to the template and the substrate. As used herein "activating light" means light that may affect a chemical change. Activating light may include ultraviolet light (e.g., light having a wavelength between about 300 nm to about 400 nm), actinic light, visible light or infrared light. Generally, any wavelength of light capable of affecting a chemical change may be classified as activating. Chemical changes may be manifested in a number of forms. A chemical change may include, but is not limited to, any chemical reaction that causes a polymerization or a cross-linking reaction to take place. The activating light may be passed through the template prior to reaching the composition. In this manner the polymerizable composition may be cured to form structures complementary to the structures formed on the template. Alternatively, the polymerizable composition may be cured by applying heat to the composition, while an electric field is applied to the template and the substrate.

[0009] After the polymerizable composition is cured, the structures may be further defined by etching the cured polymerizable composition. Etching may improve the aspect ratio of the structures. Any of the commonly used etching techniques may be used, including reactive ion etching.

[0010] In one embodiment, the template may be positioned less than about 1μm from the polymerizable composition. The substrate should therefore have a planarity of less than about 1μm, preferable less than about 0.25μm. As used herein planarity is defined as the variance in curvature over the surface of the substrate. For example, a planarity of 1μm indicates that the curvature of the surface varies by 1μm above and/or below a center point which defines a planar surface.

[0011] To achieve a surface having a planarity of less than about 1μm, the substrate may be placed on an apparatus configured to alter the shape of the substrate. The apparatus may include a holder configured to couple to and support the substrate. The apparatus may also include a plurality of pressure application devices coupled to the holder. The pressure application devices may be configured to apply a deforming force to the holder such that the shape of the holder is altered. The substrate may be coupled to the holder such that the changes in the shape of the holder may be imparted to the substrate. In this manner, the planarity of the substrate may be altered to conform to the desired planarity. The apparatus may include a programmable controller. The programmable controller may include a detection device configured to determine the planarity of the substrate. The controller may further be configured to operate the pressure application devices to alter the planarity of the substrate based on the determined planarity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figs. 1A-1E illustrate a version of the imprint lithography process according to the invention;

[0013] Fig. 2 is a process flow diagram showing the sequence of steps of the imprint lithography process of Figs. 1A-1E;

[0014] Fig. 3 is a side view of a template positioned over a substrate for electric field based lithography;

[0015] Fig. 4 is a side view of a process for forming nanoscale structures using direct contact with a template;

[0016] Fig. 5 is a side view of a process for forming nanoscale structures using non-direct contact with a template;

[0017] Fig. 6 is a side view of a substrate holder configured to alter the planarity of the substrate; and

[0018] Fig. 7 is a side view of an apparatus for positioning a template over a substrate.

DETAILED DESCRIPTION OF THE INVENTION

[0019] Figures 1A thru 1E illustrate an imprint lithography process according to the invention, denoted generally as 10. In Figure 1A, a template 12 is orientated in spaced relation to a substrate 14 so that a gap 16 is formed in the space separating template 12 and substrate 14. A surface 18 of template 12 is treated with a thin layer 20 that lowers the template surface energy and assists in separation of template 12 from substrate 14. The manner of orientation including devices for controlling of gap 16 between template 12 and substrate 14 are discussed below. Next, in Figure 1B, gap 16 is filled with a substance 22 that conforms to the shape of surface 18. Preferably, substance 22 is a liquid so that it fills the space of gap 16 rather easily

without the use of high temperatures and gap 16 can be closed without requiring high pressures.

[0020] A curing agent 24, shown in Figure 1C, is applied to template 12 causing substance 22 to harden and assume the shape of the space defined by gap 16 between template 12 and substrate 14. In this way, desired features 26, shown in Figure 1D, from template 12 are transferred to the upper surface of substrate 14. A transfer layer 28 is provided directly on the upper surface of substrate 14 which facilitates the amplification of features transferred from template 12 onto substrate 14 to generate high aspect ratio features.

[0021] In Figure 1D, template 12 is removed from substrate 14 leaving the desired features 26 thereon. The separation of template 12 from substrate 14 must be done so that desired features 26 remain intact without shearing or tearing from the surface of substrate 14.

[0022] Finally, in Figure 1E, features 26 transferred from template 12, shown in Figure 1D, to substrate 14 are amplified in vertical size by the action of transfer layer 28, as is known in the use of bi-layer resist processes. The resulting structure can be further processed to complete the manufacturing process using well-known techniques. Figure 2 summarizes the imprint lithography process, denoted generally as 30, of the present invention in flow chart form. Initially, at step 32, course orientation of a template and a substrate is performed so that a rough alignment of the template and substrate is achieved. The advantage of course orientation at step 32 is that it allows pre-calibration in a manufacturing environment where numerous devices are to be manufactured with efficiency and with high production yields. For example, where the substrate

comprises one of many die on a semiconductor wafer, course alignment (step 32) can be performed once on the first die and applied to all other dies during a single production run. In this way, production cycle times are reduced and yields are increased.

[0023] Next, at step 34, the spacing between the template and substrate is controlled so that a relatively uniform gap is created between the two layers permitting the type of precise orientation required for successful imprinting. The present invention provides a device and system for achieving the type of orientation (both course and fine) required at step 34. At step 36, a liquid is dispensed into the gap between the template and substrate. Preferably, the liquid is a UV curable organosilicon solution or other organic liquids that become a solid when exposed to UV light. The fact that a liquid is used eliminates the need for high temperatures and high pressures associated with prior art lithography techniques.

[0024] At step 38, the gap is closed with fine orientation of the template about the substrate and the liquid is cured resulting in a hardening of the liquid into a form having the features of the template. Next, the template is separated from the substrate, step 40, resulting in features from the template being imprinted or transferred onto the substrate. Finally, the structure is etched, step 42, using a preliminary etch to remove residual material and a well-known oxygen etching technique to etch the transfer layer.

[0025] As mentioned above, recent imprint lithography techniques with UV curable liquids [2, 3, 4, 5] and polymers [6] have been described for preparing nanoscale structures. These techniques may potentially be

significantly lower cost than optical lithography techniques for sub-50 nm resolution. Recent research [7, 8] has also investigated the possibility of applying electric fields and van der Waals attractions between a template that possesses a topography and a substrate that contains a polymeric material to form nanoscale structures. This research has been for systems of polymeric material that may be heated to temperatures that are slightly above their glass transition temperature. These viscous polymeric materials tend to react very slowly to the electric fields (order of several minutes) making them less desirable for commercial applications.

[0026] The embodiments described herein may potentially create lithographic patterned structures quickly (in a time of less than about 1 second). The structures may have sizes of tens of nanometers. The structures may be created by curing a polymerizable composition (e.g., a spin-coated UV curable liquid) in the presence of electric fields. Curing the polymerizable composition then sets the pattern of structures on the substrate. The pattern may be created by placing a template with a specific nanometer-scale topography at a carefully controlled nanoscale distance from the surface of a thin layer of the liquid on a substrate. If all or a portion of the desired structures are regularly repeating patterns (such as an array of dots), the pattern on the template may be considerably larger than the size of the desired repeating structures.. The template may be formed using direct write e-beam lithography. The template may be used repeatedly in a high-throughput process to replicate nanostructures onto substrates. In one embodiment, the template may be

fabricated from a conducting material such as Indium Tin Oxide that is also transparent to UV light. The template fabrication process is similar to that of phase shift photomasks for optical lithography; phase shift masks require an etch step that creates a topography on the template.

[0027] The replication of the pattern on the template may be achieved by applying an electric field between the template and the substrate. Because the liquid and air (or vacuum) have different dielectric constants and the electric field varies locally due to the presence of the topography of the template, an electrostatic force may be generated that attracts regions of the liquid toward the template. At high electric field strengths, the polymerizable composition may be made to attach to the template and dewet from the substrate at certain points. This polymerizable composition may be hardened in place by polymerization of the composition. The template may be treated with a low energy self-assembled monolayer film (e.g., a fluorinated surfactant) to aid in detachment of the template the polymerized composition.

[0028] It may be possible to control the electric field, the design of the topography of the template and the proximity of the template to the liquid surface so as to create a pattern in the polymerizable composition that does not come into contact with the surface of the template. This technique may eliminate the need for mechanical separation of the template from the polymerized composition. This technique may also eliminate a potential source of defects in the pattern. In the absence of contact, however, the liquid may not form sharp, high-resolution structures that are as well defined as in the case of contact. This may be addressed

by first creating structures in the polymerizable composition that are partially defined at a given electric field. Subsequently, the gap may be increased between the template and substrate while simultaneously increasing the magnitude of the electric field to "draw-out" the liquid to form clearly defined structures without requiring contact.

[0029] The polymerizable composition may be deposited on top of a hard-baked resist material to lead to a bi-layer process. Such a bi-layer process allows for the formation of low aspect ratio, high-resolution structures using the electrical fields followed by an anisotropic etch that results in high-aspect ratio, high-resolution structures. Such a bi-layer process may also be used to perform a "metal lift-off process" to deposit a metal on the substrate such that the metal is left behind after lift-off in the trench areas of the originally created structures.

[0030] By using a low viscosity polymerizable composition, the pattern formation due to the electric field may be fast (e.g., less than about 1 sec.), and the structure may be rapidly cured. Avoiding temperature variations in the substrate and the polymerizable composition may also avoid undesirable pattern distortion that makes nano-resolution layer-to-layer alignment impractical. In addition, as mentioned above, it is possible to quickly form a pattern without contact with the template, thus eliminating defects associated with imprint methods that require direct contact.

[0031] Figure 3 depicts an embodiment of the template and the substrate designs. Template 12 may be formed from a material that is transparent to activating light produced by curing agent 24 to allow curing of substance

22, with substance 22 being a polymerizable composition, by exposure to activating light. Forming template 12 from a transparent material may also allow the use of established optical techniques to measure gap 16 between template 12 and substrate 14 and to measure overlay marks to perform overlay alignment and magnification correction during formation of the structures. Template 12 may also be thermally and mechanically stable to provide nano-resolution patterning capability. Template 12 may also include an electrically conducting material to allow electric fields to be generated at the template-substrate interface.

[0032] In one embodiment, depicted in Figure 3, a thick blank of fused silica has been chosen as the base material for template 12. Indium Tin Oxide (ITO) may be deposited onto the fused Silica. ITO is transparent to visible and UV light and is a conducting material. ITO may be patterned using high-resolution e-beam lithography. Thin layer 20 (for example, a fluorine containing self-assembly monolayer) may be coated onto template 12 to improve the release characteristics between template 12 and substance 22. Substrate 14 may include standard wafer materials such as Si, GaAs, SiGeC and InP. A UV curable liquid may be used as substance 22. Substance 22 may be spin coated onto substrate 14. An optional transfer layer 28 may be placed between substrate 14 and transfer layer 28. Transfer layer 28 may be used for bi-layer process. Transfer layer 28 material properties and thickness may be chosen to allow for the creation of high-aspect ratio structures from low-aspect ratio structures created in substance 22. An electric field may be generated between template 12 and substrate 14 by connecting the ITO to a voltage source.

[0033] In Figures 4 and 5, two variants of the above-described process are presented. In each variant, it is assumed that a desired uniform gap 16 may be maintained between template 12 and substrate 14. An electric field of the desired magnitude may be applied resulting in the attraction of substance 22 towards the raised portions of template 12. In Figure 4, gap 16 and the field magnitudes are such that substance 22 makes direct contact and adheres to template 12. A UV curing process may be used to harden substance 22 in that configuration. Once the structures have been formed, template 12 is separated from substrate 14 by either increasing gap 16 till the separation is achieved, or by initiating a peel and pull motion wherein template 12 is peeled away from substrate 14 starting at one edge of template 12. Prior to its use, template 12 is assumed to be treated with thin layer 20 that assists in the separation step.

[0034] In Figure 5, gap 16 and the field magnitudes are chosen such that substance 22 achieves a topography that is essentially the same as that of template 12. This topography may be achieved without making direct contact with template 12. A UV curing process may be used to harden substance 22 in that configuration. In both the processes of Figures 4 and 5, a subsequent etch process may be used to eliminate the residual layer of the UV cured material. A further etch may also be used if transfer layer 28 is present between substance 22 and substrate 14 as shown in Figures 4 and 5. As mentioned earlier, transfer layer 28 may be used to obtain high-aspect ratio structures from a low aspect ratio structure created in substance 22.

[0035] Figure 6 illustrates mechanical devices that may increase the planarity of the substrate. The

template may be formed from high-quality optical flats of fused-silica with Indium Tin Oxide deposited on the fused silica. Therefore, the template typically possess extremely high planarity. The substrates typically have low planarity. Sources of variations in the planarity of the substrate include poor finishing of the back side of the wafer, the presence of particular contaminants trapped between the wafer and the wafer chuck, and wafer distortions caused by thermal processing of the wafer. In one embodiment, the substrate may be mounted on a chuck whose top surface shape may be altered by a large array of piezoelectric actuators. The chuck thickness may be such that accurate corrections in surface topography of up to a few microns may be achieved. The substrate may be mounted to the chuck such that it substantially conforms to the shape of the chuck. Once the substrate is loaded on to the chuck, a sensing system (e.g., an optical surface topography measurement system) may be used to map the top surface of the substrate accurately. Once the surface topology is known, the array of piezoelectric actuators may be actuated to rectify the topography variations such that the upper surface of the substrate exhibits a planarity of less than about 1μm. Since the template is assumed to be made from an optically flat material, this leads to template and substrate that are high quality planar surfaces.

[0036] The mechanical device in Figure 7 may be used to perform a high-resolution gap control at the template-substrate interface. This device may control two tilting degrees of freedom (about orthogonal axes that lie on the surface of the template) and the vertical translation degree of freedom of the template. The magnitude of the gap between the template and the substrate may be

measured in real-time. These real-time measurements may be used to identify the corrective template motions required about the tilting degrees of freedom and the vertical displacement degree of freedom. The three gap measurements may be obtained by using a broadband optical interferometric approach that is similar to the one used for measuring thicknesses of thin films and thin film stacks. This approach of capacitive sensing may also be used for measuring these three gaps.

[0037] Further modifications and alternative embodiments of various aspects of the invention will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims.

REFERENCES

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